REVIEW OF EXPERIMENTAL RESULTS ON RARE RADIATIVE, SEMILEPTONIC AND LEPTONIC B DECAYS

Thomas SCHIETINGER
Laboratory for High-Energy Physics, Ecole Polytechnique Fédérale, CH-1015 Lausanne, Switzerland

We review recent experimental progress in the domain of rare radiative, semileptonic and leptonic B decays. The statistical precision attained for these decays has reached a level where they start to impose meaningful constraints on the Cabibbo-Kobayashi-Maskawa matrix, which are complementary to those obtained from hadronic decays. While the current data indicate no deviations from Standard Model predictions, there is still some room for new physics in these decays.

Rare B decays to photons and leptons are among the cleanest probes of the flavour sector of the Standard Model (SM) available to present experiments. In particular, these decays have the potential of revealing the existence of new couplings not present in the SM. The field has seen tremendous progress in the last few years, thanks to the large data samples accumulated by the two asymmetric B factories, *BABAR* and Belle operating at the PEP-II and KEKB e^+e^- colliders, respectively, at a centre-of-mass energy corresponding to the mass of the $\Upsilon(4S)$ resonance.

Please note that *all branching fractions given in this review are in units of 10^{-6}* and all limits are to be understood at 90% confidence level. The symbol ℓ stands for all three charged leptons (e, μ and τ), unless otherwise specified. The first and second uncertainties quoted on measurements are statistical and systematic, respectively.

1 Radiative penguin decays

1.1 $b \to s\gamma$ inclusive

The primary motivation for inclusive $b \to s\gamma$ measurements is the search for effects from physics beyond the SM. The branching fraction directly probes the Wilson coefficient C_7 (see also Sec. 2), whereas the direct CP asymmetry is sensitive to new phases appearing in the decay

Table 1: Recent $b \to s\gamma$ inclusive branching fraction measurements, as reported by the experiments. The errors are statistical, systematic, and shape-function systematic (from the extrapolation below the photon energy cut-off).

Collaboration	method	$\mathcal{B}$ measurement	E_γ cut-off [GeV]	comment
CLEO [1]	incl.	$321 \pm 43 \pm 27^{+18}_{-10}$	2.0	
Belle [2]	incl.	$355 \pm 32^{+30}_{-31}{}^{+11}_{-7}$	1.8	
Belle [3]	semi-incl.	$336 \pm 53 \pm 42^{+50}_{-54}$	2.24	16 modes
BABAR [4]	incl.	$367 \pm 29 \pm 34 \pm 29^{a}$	1.9	lepton-tagged
BABAR [5]	semi-incl.	$335 \pm 19^{+56}_{-41}{}^{+4}_{-9}$	1.9	38 modes

[a] The branching fraction is not extrapolated below the photon energy cut-off. The third error in this case refers to a model dependence in the efficiency evaluation.

loop. Moreover, $b \to s\gamma$ is an ideal laboratory for studying the dynamics of the b-quark inside the B meson: since the motion of the b-quark inside the B meson is universal, information gained from a measurement of the energy spectrum of the emitted photon in $b \to s\gamma$ is applicable to other processes, for instance semileptonic decays.

Experimentally, two methods are used to extract the $b \to s\gamma$ (more precisely: $B \to X_s\gamma$) signal. In the first, fully inclusive method, events containing a hard photon consistent with $B \to X_s\gamma$ are selected. The resulting very large backgrounds, primarily from $q\bar{q}$ continuum events are suppressed as much as possible using sophisticated techniques based on event-shape and energy-flow variables, and then subtracted by use of off-resonance data taken below the $\Upsilon(4S)$ resonance. Particularly effective suppression of continuum backgrounds is afforded by the requirement of a high-p_t lepton, signaling the semileptonic decay of the accompanying B meson, as applied by *BABAR*. In the second, semi-inclusive method, the $B \to X_s\gamma$ rate is determined from a sum of exclusive modes with an extrapolation procedure to take account of the unobserved modes (modes containing K_L for instance). This extrapolation, which is based on the assumption of isospin symmetry and Monte Carlo (MC) simulation, contributes the largest systematic uncertainty in this method.

The most recent measurements are summarized in Table 1. The Heavy Flavor Averaging Group [6] (HFAG) has recently issued a new average using a common shape function [7] for the extrapolation to lower photon energies and taking into account the correlated error from $b \to d\gamma$:

$$\mathcal{B}(b \to s\gamma) = 355 \pm 24^{+9}_{-10} \pm 3, \tag{1}$$

for a photon cut-off energy $E_\gamma > 1.6$ GeV. The errors on this average are experimental (combined statistical and systematic), systematic due to the shape function, and systematic due to the $d\gamma$ fraction. Comparing with the corresponding value from theory,[8] $\mathcal{B}(b \to s\gamma) = 357 \pm 30$, we cannot help being impressed by the agreement—or depressed, if the goal is to find new physics!

Since significant improvements in precision cannot be expected on either the experimental or the theoretical side, the focus in $b \to s\gamma$ studies has shifted towards the measurement of the photon energy spectrum, which gives direct experimental access to parameters that can be related to the mass and momentum of the b-quark inside the B-meson and are therefore of great interest in many areas of B physics and beyond. CLEO,[1] *BABAR* [4] and Belle [2] have published spectra in the $\Upsilon(4S)$ rest frame that are, in that order, based on increasing data samples and going to lower and lower photon energy cutoffs. The semi-inclusive analysis published by *BABAR* [5] allows a spectrum measurement in the B rest frame (via the invariant mass of the strange hadronic recoil system). The spectrum obtained by this method is therefore free from the smearing due to the B momentum and profits from a much better energy resolution provided by the tracks of the hadronic recoil rather than the electromagnetic calorimeter.

As for the CP asymmetry measured in inclusive $b \to s\gamma$, neither *BABAR* [9] ($A_{CP} = (2.5 \pm 5.0 \pm 1.5)\%$) nor Belle [10] ($A_{CP} = (0.2 \pm 5.0 \pm 3.0)\%$) reports significant asymmetries from their semi-inclusive analyses, in accordance with SM predictions. A new result from *BABAR* based on its fully inclusive lepton-tagged analysis [4] (which does not distinguish $b \to s\gamma$ from $b \to d\gamma$) gives $(-11.0 \pm 11.5 \pm 1.7)\%$ for the CP-asymmetry in $b \to [s+d]\gamma$. Note that in the limit of U-spin symmetry, this asymmetry is strictly zero by unitarity in the SM.[11]

1.2 $b \to s\gamma$ exclusive

On the exclusive front, the kaon resonance modes $B \to K^*(892)\gamma$ (CLEO,[12] *BABAR*,[13] and Belle [14]), $B \to K_1(1270)\gamma$, (Belle [15]) and $B \to K_2^*(1430)\gamma$ (CLEO,[12] Belle,[16] and *BABAR* [17]) are by now well established. The measured branching fractions are in good agreement with, yet more precise than, theoretical predictions.

The list of established decays of the type $B \to K^{(*)}X\gamma$, where X stands for one or more flavourless mesons is also growing longer: Apart from $K\pi\gamma$, $K\pi\pi\gamma$ and $K^*\pi\gamma$,[16] it also includes $K\eta\gamma$ (Belle [18] and *BABAR* [19]) and $K\phi\gamma$ (Belle [20]), where most of these channels have been found to be produced via resonances. Most noteworthy among the newer results are the *BABAR* analyses on $B \to K\eta^{(\prime)}\gamma$ and $B \to K\pi\pi\gamma$, both based on 232M $B\overline{B}$ pairs: *BABAR* reports the first observation [19] of the neutral decay $B^0 \to K^0\eta\gamma$ and gives the very first limits on the channel $B \to K\eta'\gamma$, which is expected to be suppressed with respect to $B \to K\eta\gamma$ due to the well-known destructive interference of penguin diagrams. The $B \to K\pi\pi\gamma$ study [21] performed by *BABAR* yielded the first observations of the channels $B^0 \to K^+\pi^-\pi^0\gamma$ and $B^+ \to K^0\pi^+\pi^0\gamma$. These channels are of interest for a measurement of the polarization of the photon emitted in the $b \to s\gamma$ process, see Sec. 1.3.

The search for direct CP violation in exclusive radiative decays has reached the few-percent level in the channel $B \to K^*(892)\gamma$.[13,14] The latest HFAG average [6] reads $A_{CP}(B \to K^*(892)\gamma)$ $= (-1.0 \pm 2.8)\%$. A new result from *BABAR* is $A_{CP}(B^+ \to K^+\eta\gamma) = (-9 \pm 12 \pm 1)\%$.[19]

In short, Belle has been leading in this domain, but *BABAR* is rapidly catching up!

1.3 Photon polarization in $b \to s\gamma$

The polarization of the photon emitted in the $b \to s\gamma$ transition provides an important test of the SM, which predicts a mostly left-handed photon.[22,23] The two most promising methods to access this polarization experimentally at the B factories rely either on B^0-$\overline{B}^0$ interference [22] or on interference effects in decays to higher kaon resonances [24] producing $K\pi\pi^0$. In the first method, the time-dependent interference between B^0 and $\overline{B}^0$ decaying to the final state $K_S\pi^0\gamma$ (where $K_S\pi^0$ may or may not be resonant [25]) is expected to be suppressed for a polarized photon, since in that case the final state is no longer CP invariant. The reconstruction of the $K_S\pi^0\gamma$ vertex is experimentally challenging, but possible by intersecting the reconstructed K_S momentum direction with the beam envelope. The most recent measurements of the S parameter describing the interference (equivalent to $\sin(2\phi_1)$ or $\sin(2\beta)$ in $b \to c\bar{c}s$ transitions) indeed seem to favour a small value (*BABAR* [26] measures $S_{K^{*0}\gamma} = -0.21 \pm 0.40 \pm 0.05$ on a 232M $B\overline{B}$ sample, Belle [27] has $S_{K_S\pi^0\gamma} = 0.08 \pm 0.41 \pm 0.10$ from 386M $B\overline{B}$), but are not precise enough yet to put significant constraints on the photon polarization. As for the other method, the recent *BABAR* study [21] of $B \to K\pi\pi^0\gamma$ reveals a resonance structure that is rather difficult to disentangle, thus precluding a measurement of the photon polarization at this time. In particular there is no clear evidence yet of the $K_1(1400)$ resonance, a prerequisite for the method.

We conclude that constraining the photon polarization in the $b \to s\gamma$ transition remains an elusive goal for the B factories even with roughly half their expected final statistics available. Since other proposed methods, based on photon conversion [28] or interference with radiative charmonium decays [29] require even larger data samples, we may well have to wait for a Super-B factory to obtain a definitive answer. On the other hand, this may represent a good opportunity for experiments at the LHC, where radiative decays of Λ_b baryons [30] present an interesting approach, in particular if they are sufficiently polarized.[31] Further constraints on right-handed currents in $b \to s\gamma$ may come from $B \to K^* \ell^+ \ell^-$ decays.[32] First efforts to this end have been presented by *BABAR* very recently.[33]

1.4 $b \to d\gamma$

The quark transition $b \to d\gamma$ is the Cabibbo-Kobayashi-Maskawa-(CKM-)suppressed counterpart of $b \to s\gamma$, therefore expected at a rate smaller by a factor $|V_{td}/V_{ts}|^2 \approx 0.04$. An additional weak annihilation diagram also contributes to the exclusive decay $B^+ \to \rho^+\gamma$, slightly complicating the extraction of $|V_{td}/V_{ts}|^2$ from branching fraction measurements.

In 2005, Belle announced the first observation [34] of the $b \to d\gamma$ transition with a data sample equivalent to 386M $B\overline{B}$ pairs. The analysis makes use of very sophisticated background-suppression techniques including π^0 and η rejection, the requirement of spatial vertex separation between the two B mesons and application of a flavour-tagging algorithm to distinguish $B\overline{B}$ from continuum events. The background discriminating variables are combined with an event-shape Fisher discriminant to form a signal-background likelihood ratio. A flavour-tag-quality dependent cut is then applied on this likelihood ratio. The mode $B^0 \to \rho^0\gamma$ is observed with a significance of 5.2σ, $\mathcal{B}(B^0 \to \rho^0\gamma) = 1.25^{+0.37+0.07}_{-0.33-0.06}$, whereas the corresponding charged decay is only seen at 1.6σ significance, $\mathcal{B}(B^+ \to \rho^+\gamma) = 0.55^{+0.42+0.09}_{-0.36-0.08}$, in apparent contradiction to the expectation from isospin invariance. The probability of observing an isospin violation this large or larger is evaluated to be 4.9%. Theoretically, an isospin violation of $\pm 10\%$ is expected. A combined fit of $\rho^+\gamma$, $\rho^0\gamma$ and $\omega\gamma$ candidate events for an isospin-averaged rate gives $\overline{\mathcal{B}}(B \to [\rho,\omega]\gamma) = 1.32^{+0.34+0.10}_{-0.31-0.09}$, with a significance of 5.1σ. From this and by use of the formula

$$\frac{\overline{\mathcal{B}}(B \to [\rho,\omega]\gamma)}{\mathcal{B}(B \to K^*\gamma} = \left|\frac{V_{td}}{V_{ts}}\right|^2 \left(\frac{1 - m_\rho^2/M_B^2}{1 - m_{K^*}^2/M_B^2}\right)^3 \zeta^2(1 + \Delta R), \tag{2}$$

where $\zeta = 0.85 \pm 0.10$ is the relevant form factor ratio and $\Delta R = 0.1 \pm 0.1$ parameterizes the $SU(3)$ breaking due to the weak annihilation diagram, Belle obtains $|V_{td}/V_{ts}| = 0.199^{+0.026}_{-0.025}$(exp.) $^{+0.018}_{-0.015}$(theor.), in good agreement with global CKM fits.

BABAR has performed a similar analysis on a data sample containing 211M $B\overline{B}$ pairs.[35] They use a neural network to combine various background suppression variables. The obtained branching fractions are not significant. For the isospin-averaged branching fraction, the upper limit $\overline{\mathcal{B}}(B \to [\rho,\omega]\gamma) < 1.2$ is given, which translates to $|V_{td}/V_{ts}| < 0.19$.

2 Semileptonic penguin decays

The physics of[a] $b \to s\ell^+\ell^-$ is governed by the Wilson coefficients C_7, C_9 and C_{10}, which describe the strengths of the corresponding short-distance operators in the effective Hamiltonian, i.e. the electromagnetic operator O_7 and the semileptonic vector and axialvector operators O_9 and O_{10}, respectively.[36] The Wilson coefficients are experimental observables. Contributions from new physics appear in the experiment as deviations from the SM values, which have been calculated to next-to-next-to-leading order (NNLO).

Our experimental knowledge on the Wilson coefficients comes from the inclusive $b \to s\gamma$ branching fraction (Sec. 1.1), which determines the absolute value of C_7 to about 20% accuracy, but not its sign, and from the inclusive $b \to s\ell^+\ell^-$ branching fraction, which constrains C_9 and C_{10} to an annular region in the C_9-C_{10} plane,[37] but gives no information on the individual signs and magnitudes of these coefficients. To further pin down the values of these coefficients, it is

[a]Throughout this section, ℓ stands for μ and e only.

necessary to exploit interference effects between the contributions from different operators. This is possible in $b \to s\ell^+\ell^-$ decays by evaluating the differential inclusive decay rate as a function of the lepton invariant mass, $m^2_{\ell\ell} = q^2$ (Sec. 2.1), or by measuring the forward-backward asymmetry in the exclusive decay $B \to K^*\ell^+\ell^-$ (Sec. 2.3).

2.1 $b \to s\ell^+\ell^-$ inclusive

Measurements of the inclusive $b \to s\ell^+\ell^-$ decay rate have been published by Belle [38] and *BABAR*,[39] who also reports a direct CP asymmetry compatible with zero. The partial $b \to s\ell^+\ell^-$ decay rate in the lepton invariant mass range below the J/ψ resonance is sensitive to the sign of C_7.[40] A recent compilation [41] of Belle [38] and *BABAR* [39] data shows that the currently available data clearly favour a negative sign for C_7, as predicted by the SM.

2.2 $b \to s\ell^+\ell^-$ exclusive

Five of the eight individual $B \to K^{(*)}\ell^+\ell^-$ modes have been established by now, the exceptions being $K^0e^+e^-$, $K^{*+}e^+e^-$ and $K^{*+}\mu^+\mu^-$. The charge and lepton-flavour averaged branching fractions obtained by *BABAR* are[33] $\mathcal{B}(B \to K\ell^+\ell^-) = 0.34 \pm 0.07 \pm 0.02$ and $\mathcal{B}(B \to K^*\ell^+\ell^-) = 0.78^{+0.19}_{-0.17} \pm 0.11$, the Belle results read [42] $\mathcal{B}(B \to K\ell^+\ell^-) = 0.550^{+0.075}_{-0.070} \pm 0.027$ and $\mathcal{B}(B \to K^*\ell^+\ell^-) = 1.65^{+0.23}_{-0.22} \pm 0.10$, where we have combined systematic and model-dependence errors. The striking phenomenon that the Belle values are higher by almost a factor of two with respect to *BABAR*'s is present in all individual modes with significant yields, but is probably attributable to statistics. Both experiments have searched for asymmetries with respect to lepton flavour, charge and isospin, so far without finding any surprises.

2.3 Forward-backward asymmetry in $B \to K^*\ell^+\ell^-$

The forward-backward asymmetry in $B \to K^*\ell^+\ell^-$ decays is defined as

$$A_{\rm FB}(q^2) = \frac{\Gamma(q^2, \cos\theta_{B\ell^-} > 0) - \Gamma(q^2, \cos\theta_{B\ell^-} < 0)}{\Gamma(q^2, \cos\theta_{B\ell^-} > 0) + \Gamma(q^2, \cos\theta_{B\ell^-} < 0)}, \tag{3}$$

where $\theta_{B\ell^-}$ is the angle between the momenta of the negative lepton and the B meson in the dilepton rest frame (positive lepton in the case of $\overline{B}$). It is a non-trivial function of q^2 due to the interference between vector (C_7, C_9) and axial-vector (C_{10}) couplings arising from the relevant penguin and box diagrams. In other words, by probing the interference between contributions from γ, W and Z exchanges, $A_{\rm FB}$ allows us to put to the test the very foundations of the Standard Model of electroweak interactions!

A recent analysis by Belle [43] using a data sample containing 386M $B\overline{B}$ pairs finds 114 ± 13 signal $B \to K^*\ell^+\ell^-$ decays with $K^* \to K^+\pi^-$, $K_S\pi^+$ and $K^+\pi^0$ and measures $A_{\rm FB}$ for the first time. The integrated asymmetry is found to be $0.50 \pm 0.15 \pm 0.02$ (3.4σ significance) and a fit to the double differential decay width $(1/\Gamma)d^2\Gamma/dq^2 d\cos\theta_{B\ell^-}$ on 8 event categories (signal, 3 cross-feeds and 4 backgrounds) is used to extract ratios of Wilson coefficients. To facilitate comparison with various extensions of the SM, the evaluation is done for the leading-order terms A_7, A_9 and A_{10} of the Wilson coefficients, thus assuming that the higher-order corrections are the same as in the SM. Since A_7 is known experimentally up to a sign from the $b \to s\gamma$ branching fraction and $A_{\rm FB}$ is not sensitive to that parameter, it is fixed to its (experimentally confirmed) SM value [44] in the fit ($A_7 = -0.330$), and the results are expressed as the ratios $A_9/A_7 = -15.3^{+3.4}_{-4.8} \pm 1.1$ (SM: -12.3) and $A_{10}/A_7 = -10.3^{+5.2}_{-3.5} \pm 1.8$ (SM: 12.8), in excellent agreement with the SM values given in brackets. The same fit with a sign-flipped A_7 gives very similar results. For A_7 left free within the experimentally allowed region, the product of the two ratios is constrained to be in the interval $-1.40 \times 10^3 < A_9A_{10}/A_7^2 < -26.4$ at 95% confidence level, i.e. new physics scenarios with positive $A_9 A_{10}$ are excluded at such confidence. As a cross-check Belle has also measured the forward-backward asymmetry in the decay $B^+ \to K^+\ell^+\ell^-$, for which no asymmetry is expected (no vector interference). The measured integrated asymmetry in that channel, $0.10 \pm 0.14 \pm 0.01$, is indeed compatible with zero.

At this conference *BABAR* has released its first measurements of angular distributions in $B \to K^{(*)}\ell^+\ell^-$ decays using a data sample comprising 229M $B\overline{B}$ decays. The study includes CP and lepton asymmetries, as well as a measurement of the K^* longitudinal polarization in $B \to K^*\ell^+\ell^-$ decays. For the details and results of this analysis we refer to the corresponding *BABAR* publication,[33] which has become available shortly after the conference.

2.4 $b \to s\nu\bar{\nu}$

The transition analog to $b \to s\ell^+\ell^-$ with neutral leptons in the final state, $b \to s\nu\bar{\nu}$, is theoretically much cleaner than its charged counterpart, thanks to the absence of the photon penguin diagram and hadronic long-distance effects (charmonium resonances). From the experimental point of view the modes mediated by $b \to s\nu\bar{\nu}$ are extremely challenging due to the presence of two neutrinos in the final state. Searches for such modes at the B factories are therefore based on the so-called "recoil method": events are selected in which one B meson is fully reconstructed in a hadronic or semileptonic mode. These events then provide an extremely clean environment to search for the decay in question, at the expense of a rather low efficiency.

The only exclusive decay of this category that has been searched for at the B factories is $B^+ \to K^+\nu\bar{\nu}$. Using a sample of 89M $B\overline{B}$ pairs, *BABAR* sets the limit $\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) < 52$ on the branching fraction.[45] The analysis uses about 480k $B^+ \to D^{(*)0}\ell^+\nu$ and 180k $B^+ \to D^{(*)0}X^+_{\rm had}$ decays, where $X^+_{\rm had}$ stands for up to five pions or kaons. After finding exactly one opposite-charged kaon in the event remainder, the primary selection criterion is a limit on the extra energy found in the electromagnetic calorimeter, $E_{\rm extra} < 200$ MeV. The Belle search[46] for $B^+ \to K^+\nu\bar{\nu}$ is essentially a by-product of their search for $B^+ \to \tau^+\nu_\tau$, which we will describe in Sec. 3.1. The limit obtained with 275M $B\overline{B}$ pairs is $\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) < 36$. The experimental limits are still an order of magnitude away from the SM value,[47] $\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) = 3.8^{+1.2}_{-0.6}$.

3 Annihilation tree and penguin decays to leptons and photons

3.1 $B^+ \to \ell^+\nu$

The leptonic decays of charged B mesons give direct access to the product of the decay constant f_B and the CKM-matrix element V_{ub}, according to

$$\mathcal{B}(B^+ \to \ell^+\nu_\ell) = \frac{G_F^2 m_B}{8\pi} m_\ell^2 \left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B. \tag{4}$$

Allowing for decay amplitudes beyond the SM, measurements of these decays give stringent limits on important parameters of such SM extensions, e.g. the mass of the charged Higgs boson and $\tan\beta$ in the minimal supersymmetric SM, or leptoquark masses in Pati-Salam models.

The most recent efforts have concentrated on $B^+ \to \tau^+\nu_\tau$, where an observation seems tantalizingly close. The presence of one or more neutrinos in the final state again implies that experimental searches are limited to the recoils of fully reconstructed B decays. The Belle analysis [46] starts from a sample of about 400k $B^+ \to D^{(*)0}h^+$ and $D^{(*)0}D_s^{(*)+}$ events ($h = \pi, K$) selected in 275M $B\overline{B}$ pairs, whereas *BABAR* [48] uses a similar number of semileptonic $B^+ \to D^{(*)0}\ell^+\nu$ events (from 232M $B\overline{B}$ pairs). Decays of the types $\tau \to \mu(e)\nu\bar{\nu}$, $\pi\nu$, $\pi\pi^0\nu$, and $\pi\pi\pi\nu$ are then searched for in the event remainders. The final event selection is based on the extra energy present in the electromagnetic calorimeter. So-called double-tag events (i.e.

fully reconstructed $\Upsilon(5S)$ decays) are used to validate the simulation of this quantity. The limits obtained are 180 (Belle [b]) and 260 (*BABAR*, combined with a previous analysis [50] based on hadronic B decays). Both experiments report positive, but still insignificant mean values, 81^{+58}_{-45} and 130^{+58}_{-45}, respectively, which HFAG averages to 92^{+51}_{-41}, a number which coincidentally lies very close to the SM prediction [48] of 93 ± 39.

The related decays $B^+ \to \mu^+\nu_\mu$ and $B^+ \to e^+\nu_e$ are helicity suppressed with respect to $B^+ \to \tau^+\nu_\tau$ by factors of 223 and 10^7, respectively (Eq. 4). No new limits on these decay channels have been reported since 2004. For the sake of completeness, we note that the best limits so far have been reported (but not published) by Belle, $\mathcal{B}(B^+ \to \mu^+\nu_\mu) < 2.0$ (152M $B\overline{B}$) [51] and $\mathcal{B}(B^+ \to e^+\nu_e) < 5.4$ (65M $B\overline{B}$).[52] Belle also gives [51] $\mathcal{B}(B^+ \to \mu^+\nu_\mu\gamma) < 23$ and $\mathcal{B}(B^+ \to e^+\nu_e\gamma) < 22$. *BABAR* has published the limit [53] $\mathcal{B}(B^+ \to \mu^+\nu_\mu) < 6.6$.

3.2 $B^0 \to \ell^+\ell^-$

An important advance in this category has been achieved by *BABAR* by establishing the very first limit [54] on the decay $B^0 \to \tau^+\tau^-$. This previously unconstrained decay represented a big loophole for theorists.[55] An experimental limit constrains in particular leptoquark couplings and $\tan\beta$ enhancements in Supersymmetry. The 2–4 neutrinos in the final state render the experimental search extremely difficult. The *BABAR* analysis starts from 280k fully reconstructed $B^0 \to D^{(*)}X$ decays, where X stands for a combination of charged and neutral pions and kaons. Decay products of two "simple" τ decays are then searched for in the event remainder, i.e. two τ decays with only one charged particle each: $\tau \to \mu(e)\nu\bar{\nu}$, $\pi\nu$ and $\rho\nu$, which together cover 51% of all $\tau^+\tau^-$ decays. After rejecting events containing identified neutral and charged kaons, the kinematics of the charged daughters and the residual energy in the electromagnetic calorimeter are fed into a neural network to separate signal from background. The limit obtained in this way is $\mathcal{B}(B^0 \to \tau^+\tau^-) < 3400$, four orders of magnitude above the SM value.

Concerning decays to pairs of lighter leptons, the best limits from the B factories come from *BABAR*, $\mathcal{B}(B^0 \to \mu^+\mu^-) < 0.083$ and $\mathcal{B}(B^0 \to e^+e^-) < 0.061$, obtained with 120M $B\overline{B}$ pairs,[56] representing an improvement of over a factor of two with respect to the previous Belle limits.[57] The Tevatron experiments have now taken the lead in the search for $B \to \mu^+\mu^-$: CDF reports the limits [58] $\mathcal{B}(B^0 \to \mu^+\mu^-) < 0.039$ and $\mathcal{B}(B^0_s \to \mu^+\mu^-) < 0.15$ obtained with 364 pb^{-1} of data, while DØ (not having sufficient mass resolution to distinguish B^0 from B^0_s) gives [59] $\mathcal{B}(B^0_s \to \mu^+\mu^-) < 0.3$ (300 pb^{-1}). A combination of Tevatron data,[60] taking into account common systematics, finds the limits $\mathcal{B}(B^0 \to \mu^+\mu^-) < 0.032$ and $\mathcal{B}(B^0_s \to \mu^+\mu^-) < 0.12$, which already put stringent constraints [61] on some supersymmetric models!

3.3 $B^0 \to \nu\bar{\nu}$

The decay $B^0 \to \nu\bar{\nu}$ is essentially forbidden in the SM, hence any evidence for invisible decays of B mesons would point to exotic phenomena such as neutralinos or large extra dimensions. The only limit so far is the one published by *BABAR*,[62] $\mathcal{B}(B^0 \to \nu\bar{\nu}) < 220$. It is based on the analysis of the recoils of 126k reconstructed $B \to D^{(*)}\ell\nu$ events (from 88.5M $B\overline{B}$ pairs). By looking for one energetic photon in the same events, *BABAR* also obtains a limit for the associated radiative decay, $\mathcal{B}(B^0 \to \nu\bar{\nu}\gamma) < 47$.

3.4 $B^0 \to \gamma\gamma$

Like the other decays mediated by annihilation diagrams, the purely radiative decay of the B^0 could receive enhancements from the exchange of charged Higgs bosons or more exotic charged

[b] A few weeks after this conference, the Belle collaboration has announced evidence for $B^+ \to \tau^+\nu_\tau$.[49]

particles. Belle has recently published its first search for this channel, based on a data sample equivalent to 111M $B\overline{B}$ pairs.[63] The result, $\mathcal{B}(B^0 \to \gamma\gamma) < 0.62$, improves on a very early *BABAR* limit,[64] but is still about a factor 20 away from the SM prediction.

Applying a similar analysis to the 1.86 fb^{-1} of data obtained from a short (3 days) engineering run at the $\Upsilon(5S)$, Belle has set a preliminary limit on the corresponding B_s^0 decay,[65] $\mathcal{B}(B_s^0 \to \gamma\gamma) < 56$. Note that the branching fraction predicted by the SM for this channel is around 1.2, a level that would be within reach of a few-months long run at the $\Upsilon(5S)$!

4 Summary

To summarize we note that in the past couple of years the availability of data samples containing several hundred million $B\overline{B}$ pairs at the B factories has brought about decisive advances in the field of radiative and leptonic rare B decays: while the study of the $b \to s\gamma$ transition has turned into a precision science, $b \to d\gamma$ has finally become observable; in the $b \to s\ell^+\ell^-$ sector we have moved from mere observation to the exploration of angular distributions probing for the first time the Wilson coefficients at play, and we are at the brink of observing the first purely leptonic decay of the B meson, $B^+ \to \tau^+\nu_\tau$. On top of the statistics, the experience and expertise accumulated at the B factories by now allow the experiments to tackle even the most challenging decay modes, as demonstrated by *BABAR*'s recent limit on $B^0 \to \tau^+\tau^-$.

The wealth of new data not only curbs an array of new-physics models, but also begins to add significant constraints on the CKM parameters ($|V_{ub}|$ from $B^+ \to \tau^+\nu_\tau$, $|V_{td}/V_{ts}|$ from $B \to [\rho,\omega]\gamma$ and $B \to K^*\gamma$), in addition and complementary to the ones obtained from hadronic decays.[66] So far, the SM still saves its bacon, but it may just be too early to tell in these channels, which remain our most promising scouts for new physics beneath the energy frontier.

Acknowledgments

I am indebted to all the members of the *BABAR* and Belle collaborations who have contributed to this review in one way or another. In particular I thank R. Faccini and J. Berryhill (*BABAR*), as well as M. Nakao and K. Ikado (Belle) for their invaluable help. This work was supported by the Swiss National Science Foundation under grant Nr. 620-066162.

References

1. CLEO Collaboration, S. Chen *et al.*, *Phys. Rev. Lett.* **87**, 251807 (2001).
2. Belle Collaboration, P. Koppenburg *et al.*, *Phys. Rev. Lett.* **93**, 061803 (2004).
3. Belle Collaboration, K. Abe *et al.*, *Phys. Lett.* B **511**, 151 (2001).
4. *BABAR* Collaboration, B. Aubert *et al.*, hep-ex/0507001.
5. *BABAR* Collaboration, B. Aubert *et al.*, *Phys. Rev.* D **72**, 052004 (2005).
6. Heavy Flavor Averaging Group, E. Barberio *et al.*, hep-ex/0603003.
7. O.L. Buchmüller, H.U. Flächer, *Phys. Rev.* D **73**, 073008 (2006).
8. A.J. Buras, A. Czarnecki, M. Misiak, J. Urban, *Nucl. Phys.* B **631**, 219 (2002).
9. *BABAR* Collaboration, B. Aubert *et al.*, *Phys. Rev. Lett.* **93**, 021804 (2004).
10. Belle Collaboration, S. Nishida *et al.*, *Phys. Rev. Lett.* **93**, 031803 (2004).
11. T. Hurth, E. Lunghi, W. Porod, *Nucl. Phys.* B **704**, 56 (2005).
12. CLEO Collaboration, T.E. Coan *et al.*, *Phys. Rev. Lett.* **84**, 5283 (2000).
13. *BABAR* Collaboration, B. Aubert *et al.*, *Phys. Rev.* D **70**, 112006 (2004).
14. Belle Collaboration, M. Nakao *et al.*, *Phys. Rev.* D **69**, 112001 (2004).
15. Belle Collaboration, Heyoung Yang *et al.*, *Phys. Rev. Lett.* **94**, 111802 (2005).
16. Belle Collaboration, S. Nishida *et al.*, *Phys. Rev. Lett.* **89**, 231801 (2002).
17. *BABAR* Collaboration, B. Aubert *et al.*, *Phys. Rev.* D **70**, 091105 (2004).
18. Belle Collaboration, S. Nishida *et al.*, *Phys. Lett.* B **610**, 23 (2005).

19. *BABAR* Collaboration, B. Aubert *et al.*, hep-ex/0603054, submitted to *Phys. Rev. Lett.*
20. Belle Collaboration, A. Drutskoy *et al.*, *Phys. Rev. Lett.* **92**, 051801 (2004).
21. *BABAR* Collaboration, B. Aubert *et al.*, hep-ex/0507031.
22. D. Atwood, M. Gronau, A. Soni, *Phys. Rev. Lett.* **79**, 185 (1997).
23. B. Grinstein, Y. Grossman, Z. Ligeti, D. Pirjol, *Phys. Rev.* D **71**, 011504 (2005).
24. M. Gronau, Y. Grossman, D. Pirjol, A. Ryd, *Phys. Rev. Lett.* **88**, 051802 (2002);
M. Gronau, D. Pirjol, *Phys. Rev.* D **66**, 054008 (2002).
25. D. Atwood, T. Gershon, M. Hazumi, A. Soni, *Phys. Rev.* D **71**, 076003 (2005).
26. *BABAR* Collaboration, B. Aubert *et al.*, *Phys. Rev.* D **72**, 051103 (2005).
27. Belle Collaboration, K. Abe *et al.*, hep-ex/0507059.
28. Y. Grossman, D. Pirjol, *J. High Energy Phys.* **0006**, 029 (2000).
29. M. Knecht, T. Schietinger, *Phys. Lett.* B **634**, 403 (2006).
30. T. Mannel, S. Recksiegel, *J. Phys. G: Nucl. Part. Phys.* **24**, 979 (1998).
31. G. Hiller, A. Kagan, *Phys. Rev.* D **65**, 074038 (2002).
32. D. Melikhov, N. Nikitin, S. Simula, *Phys. Lett.* B **442**, 381 (1998).
33. *BABAR* Collaboration, B. Aubert *et al.*, *Phys. Rev.* D **73**, 092001 (2006).
34. Belle Collaboration, D. Mohapatra *et al.*, hep-ex/0506079, submitted to *Phys. Rev. Lett.*
35. *BABAR* Collaboration, B. Aubert *et al.*, *Phys. Rev. Lett.* **94**, 011801 (2005).
36. G. Buchalla, A.J. Buras, M.E. Lautenbacher, *Rev. Mod. Phys.* **68**, 1125 (1996).
37. A. Ali, E. Lunghi, C. Greub, G. Hiller, *Phys. Rev.* D **66**, 034002 (2002).
38. Belle Collaboration, M. Iwasaki *et al.*, *Phys. Rev.* D **72**, 092005 (2005).
39. *BABAR* Collaboration, B. Aubert *et al.*, *Phys. Rev. Lett.* **93**, 081802 (2004).
40. See, for example, T. Goto, Y. Okada, Y. Shimizu, M. Tanaka, *Phys. Rev.* D **55**, 4273 (1997).
41. P. Gambino, U. Haisch, M. Misiak, *Phys. Rev. Lett.* **94**, 061803 (2005).
42. Belle Collaboration, K. Abe *et al.*, hep-ex/0410006.
43. Belle Collaboration, A. Ishikawa *et al.*, hep-ex/0603018, submitted to *Phys. Rev. Lett.*
44. H.H. Asatryan, H.M. Asatrian, C. Greub, M. Walker, *Phys. Lett.* B **507**, 162 (2001).
45. *BABAR* Collaboration, B. Aubert *et al.*, *Phys. Rev. Lett.* **94**, 101801 (2005).
46. Belle Collaboration, K. Abe *et al.*, hep-ex/0507034.
47. G. Buchalla, G. Hiller, G. Isidori, *Phys. Rev.* D **63**, 014015 (2001);
A. Faessler, T. Gutsche, M.A. Ivanov, J.G. Körner, V.E. Lyubovitskij, *Eur. Phys. J.* direct C **4**, 18 (2002).
48. *BABAR* Collaboration, B. Aubert *et al.*, *Phys. Rev.* D **73**, 057101 (2006).
49. Belle Collaboration, K. Ikado *et al.*, hep-ex/0604018, submitted to *Phys. Rev. Lett.*
50. *BABAR* Collaboration, B. Aubert *et al.*, *Phys. Rev. Lett.* **95**, 041804 (2005).
51. Belle Collaboration, K. Abe *et al.*, hep-ex/0408132.
52. Belle Collaboration, K. Abe *et al.*, BELLE-CONF-0247 (2002).
53. *BABAR* Collaboration, B. Aubert *et al.*, *Phys. Rev. Lett.* **92**, 221803 (2004).
54. *BABAR* Collaboration, B. Aubert *et al.*, hep-ex/0511015, submitted to *Phys. Rev. Lett.*
55. Y. Grossman, Z. Ligeti, E. Nardi, *Phys. Rev.* D **55**, 2768 (1997).
56. *BABAR* Collaboration, B. Aubert *et al.*, *Phys. Rev. Lett.* **94**, 221803 (2005).
57. Belle Collaboration, M.-C. Chang *et al.*, *Phys. Rev.* D **68**, 111101 (2003).
58. CDF Collaboration, A. Abulencia *et al.*, *Phys. Rev. Lett.* **95**, 221805 (2005); **95**, 249905(E) (2005).
59. D∅ Collaboration, D∅ note 4733-CONF (2005).
60. R. Bernhard *et al.* (for the CDF and D∅ Collaborations), hep-ex/0508058.
61. See, for instance, R. Dermíšek, S. Raby, L. Roszkowski, R. Ruiz de Austri, *J. High Energy Phys.* **0509**, 029 (2005).
62. *BABAR* Collaboration, B. Aubert *et al.*, *Phys. Rev. Lett.* **93**, 091802 (2004).
63. Belle Collaboration, S. Villa *et al.*, *Phys. Rev.* D **73**, 051107 (2006).
64. *BABAR* Collaboration, B. Aubert *et al.*, *Phys. Rev. Lett.* **87**, 241803 (2001).
65. A. Drutskoy, talk given at this conference.
66. CKMfitter Group, J. Charles *et al.*, *Eur. Phys. J.* C **41**, 1 (2005);
UTfit Collaboration, M. Bona *et al.*, *J. High Energy Phys.* **0507**, 028 (2005);
for the most recent results and plots, see the web sites `http://ckmfitter.in2p3.fr` (French dressing) and `http://utfit.roma1.infn.it` (Italian dressing).